BALLOON-BORNE X-RAY POLARIMETRY

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The recent discoveries of solar x-ray emission and stellar x-ray sources have led to important questions regarding the physical processes generating these highly energetic photons. To obtain a more complete understanding of the x-ray production mechanisms responsible, investigators have sought to measure the overall intensity, spectrum, time variation, and polarization of the x-ray fluxes. In particular, the polarization of the x-ray emission is strongly dependent on the source conditions. X rays produced in a hot, isotropic, optically thin plasma would be unpolarized. Such a model has been suggested for the strong stellar x-ray source Sco X-1. However, x rays produced by bremsstrahlung collisions between a stream of high energy anisotropic electrons and an ambient gas would exhibit strong linear polarization. These conditions could prevail during a solar flare, where high energy electrons accelerated in the corona stream into the denser atmosphere, collide with the cooler gas and emit the high energy x-ray flux that is often observed (Cline and Holt, 1968). The low energy photons will be polarized perpendicular to the plane formed by the incident beam and outing x-ray flux, and the high energy photons will be polarized in the plane. The synchrotron process provides a

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third possible method of producing x rays. Relativistic electrons trapped in a magnetic field will spiral around the field lines, radiating x-ray photons which are linearly polarized with their electric vector lying in the plane perpendicular to the magnetic field intensity. In this case, the plane of polarization is independent of the photon energy. This mechanisn has been considered in explaining the x-ray emission of the Crab nebula, since a similar process seems to adequately explain its polarized optical and radio emission (Woltjer, 1964). Measurements of x-ray polarization and its energy dependence would be definitive in distinguishing between the various production processes.

X-ray polarization can be detected by utilizing the angular dependence of the electron-photon incoherent scattering cross section. When the scattering angle is 90°, the photons are preferentially scattered in a direction orthogonal to the incident beam and the electric vector of the incident wave, as shown in Fig. 1. This effect can be realized in a scattering target comprised of a light element, where the electrons are loosely bound and can scatter photons incoherently. This method of detecting polarization is limited by the condition that the scattering angle must be 90° to obtain complete extinction of the photons polarized in the plane of viewing (the plane formed by the directions of the incident and scattered beams). In practice, the x-ray detector must subtend a large solid angle, and photons scattered at angles other than 90° are also detected, but this effect can be accounted for. Incoherent scattering as a method of detecting x-ray polarization has the distinct advantage over other techniques such as Bragg reflection because the cross section is essentially independent of energy. Whereas Bragg reflection can be used to measure polarization only at a single wavelength, incoherent scattering allows observation over a continuum of energies. This effect is advantageous because it increases the signal strength and enables simultaneous measurement of polarization over a range of energies.

An incoherent scattering x-ray polarimeter has been constructed and successfully flown in sounding rockets to study several stellar x-ray sources. The instrument is shown in Fig. 2. The polarimeter consists of an array of scattering blocks and x-ray detectors enclosed in an anticoincidence shield to reduce the cosmic-ray-induced background. Both the stellar and solar x-ray fluxes depend strongly on energy, diminishing rapidly at shorter wavelength. The flux from the Crab nebula, for example, obeys a power law (Boldt et al., 1969)

$$N(E)dE = 7E^{-2}dE \text{ photons/cm}^2\text{-sec-keV} \qquad (1)$$

in the range 1-500 keV. It is imperative to maximize the sensitivity of the instrument at the lowest possible energy. For this reason, lithium metal was selected as a scattering material. Photoelectric absorption varies with energy as $E^{-7/2}$, and in lithium the incoherent scattering cross section and photoelectric cross section become comparable at 8 keV. Above this energy, the polarimeter can operate efficiently. The shape of the scattering blocks was chosen to maximize the overall sensitivity. The block length is greater than one scattering length, implying that more that 70% of the incident photons will interact in the metal. The width was chosen to be small compared to a scattering length to allow photons to emerge from the sides without multiple scattering.

Proportional counters are used to detect the scattered photons. These detectors produce a signal amplitude proportional to the energy of the detected x ray, allowing pulse-height analysis and the study of the energy dependence of the x-ray polarization. Furthermore, those cosmic-ray background pulses whose amplitudes fall above the range expected for x rays can be eliminated. Proportional counters also permit the use of pulse shape discrimination to distinguish between valid x-ray events and charged-particle-induced background. The gas filling in the counters establishes the upper limit of the polarimeter energy range, and this was maximized by using three atmospheres of xenon. The overall sensitivity of the polarimeter as a function of energy is shown in Fig. 3.

Data are taken with the polarimeter by pointing the instrument at the x-ray source and rotating around the line of sight. If the x-ray flux is polarized, the counting rate in each detector will be modulated at twice the rotation frequency. The depth of modulation determines the degree of polarization. Monte Carlo calculations and laboratory tests have shown that the x-ray polarization P is related to the maximum and minimum counting rates N_{max} and N_{min} by the relation

$$P = \mu \left(\frac{N_{max} - N_{min}}{N_{max} + N_{min}} \right) \qquad (2)$$

where μ is the polarimeter modulation factor, and is equal to 3.18.

The measurement of stellar x-ray polarization is limited by the low signal intensities and the high cosmic-ray-induced background rates. A prototype of the polarimeter was flown in a balloon to assess the effectiveness of various background suppression techniques and to investigate instrumental effects which could result in a spurious polarization measurement (Wing, 1968). The polarimeter was carried to an altitude of 96,000 ft, hung vertically below the balloon, and rotated around the symmetry axis. It was found that the anticoincidence shield reduced the background rate by a factor of three. Pulse-height analysis reduced the background in the range 5 to 25 keV by another factor of three. A final background rate of 0.01 counts/keV-sec-counter was obtained. The flux from the Crab nebula in the same energy range above the atmosphere is approximately one tenth of this value. The asymmetry of the primary cosmic-ray flux, or east-west effect, was also considered. A modulation in the background rate due to this anisotropy could manifest itself as a spurious indication of polarization. Analysis of the data revealed, however, that all fluctuations in the counting rates were completely random.

Further background suppression has been obtained by utilizing pulse-shape discrimination. Charged particles passing through the counters produce long ionization trails, and the subsequent pulses rise slowly. X rays, however, are absorbed at a single point and result in quickly rising pulses. A method of distinguishing between the two types of events was developed, and data obtained in a recent rocket flight indicated that the background rate can be reduced to 0.003 counts/counter-keV-sec (Wolff, 1969).

Although the polarimeter was originally designed for use in sounding rockets, its application from balloon altitudes has been seriously considered. The development of larger balloons, with increased lifting capacity and altitude, has greatly improved the feasibility of balloon-borne x-ray polarimetry. The availability of better control systems has also been an important factor.

The primary problem in stellar x-ray polarimetry is the low intensity and strong energy dependence of the sources. For this reason, high altitude and long duration flights are essential to make meaningful measurements.

As an example of the problems involved and the results which could be obtained, we can consider the possibility of measuring the x-ray polarization of the Crab nebula with the lithium block polarimeter. Since atmospheric absorption is acute at energies below 15 keV, we have assumed an energy range of 15 to 50 keV. The efficiency of the polarimeter between 25 and 35 keV is particularly low when only xenon gas is used in the detectors because the xenon K absorption edge lies at 35 keV. If the proportional counters are filled with a mixture of 1.5 atmospheres of xenon and 1.5 atmospheres of krypton, the efficiency can be greatly increased, as shown by the broken curve in Fig. 3. However, laboratory measurements have indicated that background rejection using pulse-shape discrimination is less effective in gas mixtures.

The signal intensity for the Crab nebula, measured at the top of the atmosphere, was calculated from Eq. (1) and corrected for atmospheric absorption at various balloon altitudes. The use of the xenon-krypton mixture increased the signal intensity in the 15 to 50 keV range by 55%. The background rate assumed was based on the most recent rocket data. A study of the rocket data as a function of altitude indicated that the background rate was constant above 100,000 ft. A total background rate of 7 counts/counter-sec could be expected. The signal intensity was calculated for 125,000 ft, 140,000 ft, and 157,000 ft with the Crab nebula 10° from the zenith, corresponding to a launch from Palestine, Texas. At the lowest altitude, a rate of 0.22 counts/counter-sec would be obtained; at 140,000 ft, the signal rate would be 0.50 counts/counter-sec; and at 157,000 ft, the signal rate would be 0.84 counts/counter-sec.

The minimum polarization that can be measured is governed by the total numbers of signal and background rates obtained. Statistical fluctuations impose a lower limit on the detectable polarization, since a finite amount of completely random data will yield a non-zero result. If we refer the polarization vector to an orthogonal coordinate system and let P_1 and P_2 be the components of P along each axis, it can readily be shown that the minimum detectable polarization (in each component) is given by (Wolff, 1969)

$$3\sigma_{P_i} = 3\sqrt{2}\,\frac{\mu\sqrt{S + B}}{S} \qquad (3)$$

where S and B are the total numbers of signal and background counts. This limit means that 99% confidence can be ascribed to a result which exceeds the value calculated from Eq. (3). Since polarization is a positive definite quantity obtained from the components by the relationship

$$P = \sqrt{P_1^{\,2} + P_2^{\,2}} \quad , \qquad (4)$$

it is apparent that purely statistical fluctuation in the components will always result in a non-zero value for the apparent polarization. Even when the actual polarization is zero, a measurement of P will yield a mean value of (Wolff, 1969)

$$P = \sqrt{\frac{\pi}{2}}\,\sigma_{P_i} \quad . \qquad (5)$$

The predicted signal and background rates can now be used with Eq. (3) to obtain an estimate of the sensitivity of a balloon-borne polarimetry experiment. Since the background rate greatly exceeds the signal, it is clear that long observation periods will be required. This calculation was performed assuming 8 hours at maximum altitude with the meridian crossing in the middle of the observation period. This condition was chosen to minimize the atmospheric slant height and also to avoid possible cosmic-ray effects at large zenith angles (discussed below). By combining the signals from the 16 proportional counters, we find that the minimum detectable polarization at an altitude of 125,000 ft is 21%. At an altitude of 140,000 ft, observing for the same 8-hour period, the limit is lowered to 15%. If the experiment can be performed at 157,000 ft, a polarization as small as 10.2% could be detected.

The latter result makes balloon-borne polarimetry appear feasible if the problems inherent in long-term observations can be overcome. Current models of the Crab nebula which attribute the x-ray emission to synchrotron radiation from relativistic electrons predict that the optical and x-ray flux should have comparable polarizations. The optical emission integrated over the $1'$ diameter region of the nebula responsible for x-ray emission is 19% polarized (Oort and Walraven, 1956). Furthermore, the 2-cm radio emission from the entire nebula is 14% polarized. The only x-ray result reported to date, obtained from a rocket flight with this same polarimeter, yielded an upper limit of 27% on the x-ray polarization (Wolff et al, 1970). The proposed balloon experiment would therefore provide a substantial improvement in the sensitivity of measurements of this important quantity.

The prolonged observation times required to obtain sufficient data necessitate accurate pointing and control of the payload. The polarimeter must be pointed within 3° of the x-ray source in order to avoid instrumental effects which lead to spurious signal modulation. When the x-ray flux is incident at an angle greater than 3°, unscattered photons can directly illuminate the detectors, leading to an anomalously high counting rate. Calculations and laboratory measurements revealed that the spurious polarization induced by this effect is less than 1.5%, provided that the x-ray flux is within 2.5° of the polarimeter axis. A control system capable of pointing the payload to within a 3° radius circle of the x-ray source and maintaining a sidereal scan is therefore required. The polarimeter must also be rotated around the line of sight to average out the differences in sensitivity among the various detectors and to obtain the modulation characteristic of polarization. The payload could be equipped with a rocking assembly which would rotate the polarimeter through $\pm$ 45° while the gondola remains fixed. Finally, it would be desirable to periodically point the polarimeter away from the source to make a background measurement. Since the background rate is so crucial to the experiment, long-term drifts in the electronics which could affect the counting rate would greatly confuse the data.

A further restriction on the control system is that the angle between the polarimeter axis and the zenith be kept at a minimum. Evidence from satellite surveys has shown a substantial gamma-ray albedo from the earth's atmosphere, which is particularly strong at the horizon. If the polarimeter is aimed near the vertical, the projected area subtending this flux is minimized. The background counting rate would be higher when the instrument is pointed far from the vertical and could be subject to angular variations which could induce spurious modulation. Since the sun can also be a strong source of high energy x rays, it would be prudent to perform the experiment at night using a stellar tracking system.

The problems inherent in measuring polarization in solar x-ray emission are quite distinct from those associated with stellar sources. Under normal circumstances, the sun is not a source of high energy x rays, with a negligible flux above a few keV. During periods of solar activity, however, appreciable numbers of energetic photons, usually associated with solar flares, are emitted. Sounding rocket and satellite monitors have been used to study the intensity, spectra, and time variations of these x-ray events. A typical x-ray flare rises to a maximum in 1 to 2 min, reaching a peak energy flux in excess of 10^{-4} ergs/cm^2-sec above 7 keV, and then diminishes in 5 to 10 min. Often superimposed on this flux are short, intense bursts of high energy rays of a few seconds' duration and ranging as high as 100 keV. The slower varying component of the x-ray emission often exhibits a thermal spectrum which can be characterized by plasma temperatures as high as 10^8 °K.

Using x-ray data recently reported for a solar flare (Hudson et al, 1969), we have calculated the minimum detectable polarization in various energy intervals. The results are listed in Table I. In performing these calculations, a balloon altitude of 125,000 ft and 100 sec of data were assumed. Polarization of x-ray fluxes up to 90 keV could readily be measured.

TABLE I

MINIMUM DETECTABLE POLARIZATION FROM AN X-RAY FLARE OBSERVED AT 125,000 FT.

Energy Range (keV)	3σ Limit (%)
10-20	1.77
20-30	1.61
30-40	1.80
40-50	1.77
50-60	2.95
60-70	5.15
70-80	8.70
80-90	18.7

The primary problem in measuring x-ray flare polarization from balloons involves the frequency of occurrence of the events. The rate at which flares occur is strongly related to the state of solar activity. During times of peak activity, flares are produced several times per day, but accurate predictions cannot be made. At best, a probability of flare occurrence can be established, based on the age and number of active regions on the sun. During times of high probability, one could launch a balloon experiment and wait for a flare, but even in an 8-hour patrol the chance of detecting a flare is not great. A successful solar flare balloon program would necessitate a series of launches in conjunction with a period of intense solar activity.

In summary, it is possible to say that stellar x-ray polarimetry is feasible from balloons. With high-altitude, accurately controlled balloons, the long observation periods required to accrue adequate data can be obtained. Measurement of solar x-ray polarization, although not encumbered by the long integration periods, still requires accurate control over prolonged time intervals while waiting for an x-ray flare to occur. Both experiments could yield meaningful data regarding the mechanism responsible for x-ray production.

REFERENCES

Boldt, E., Desai, V. and Holt, S., Astrophys. J. 156, 427 (1969).

Hudson, H. S., Peterson, L. E. and Schwartz, D. A., Astrophys. J. 157, 389 (1969).

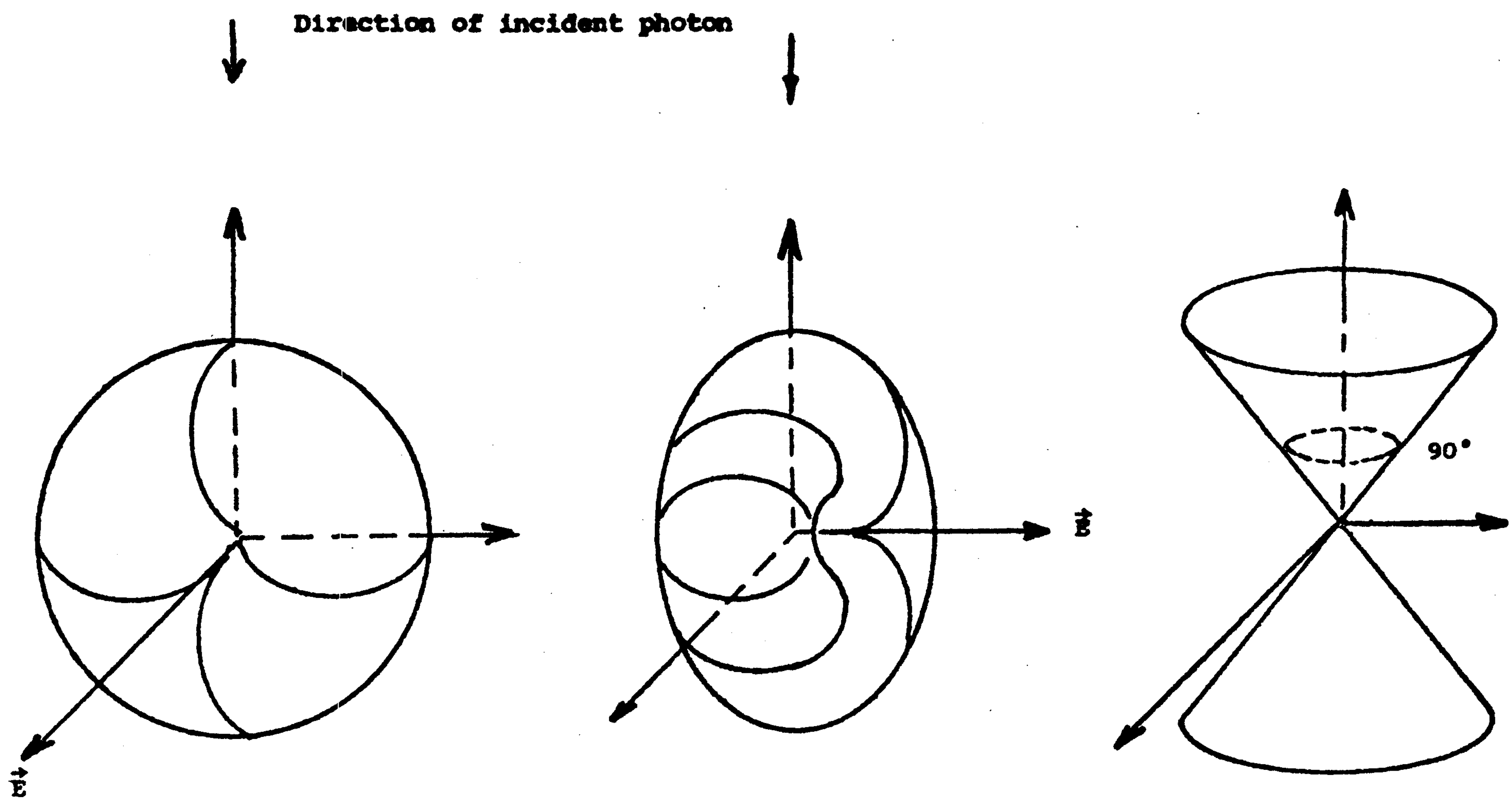
Oort, H. H. and Walraven, T., Bull. Astron. Inst. Neth. 12, 285 (1956).

Wing, T., Ph.D. Thesis, Dept. of Physics, Columbia University, New York (1968).

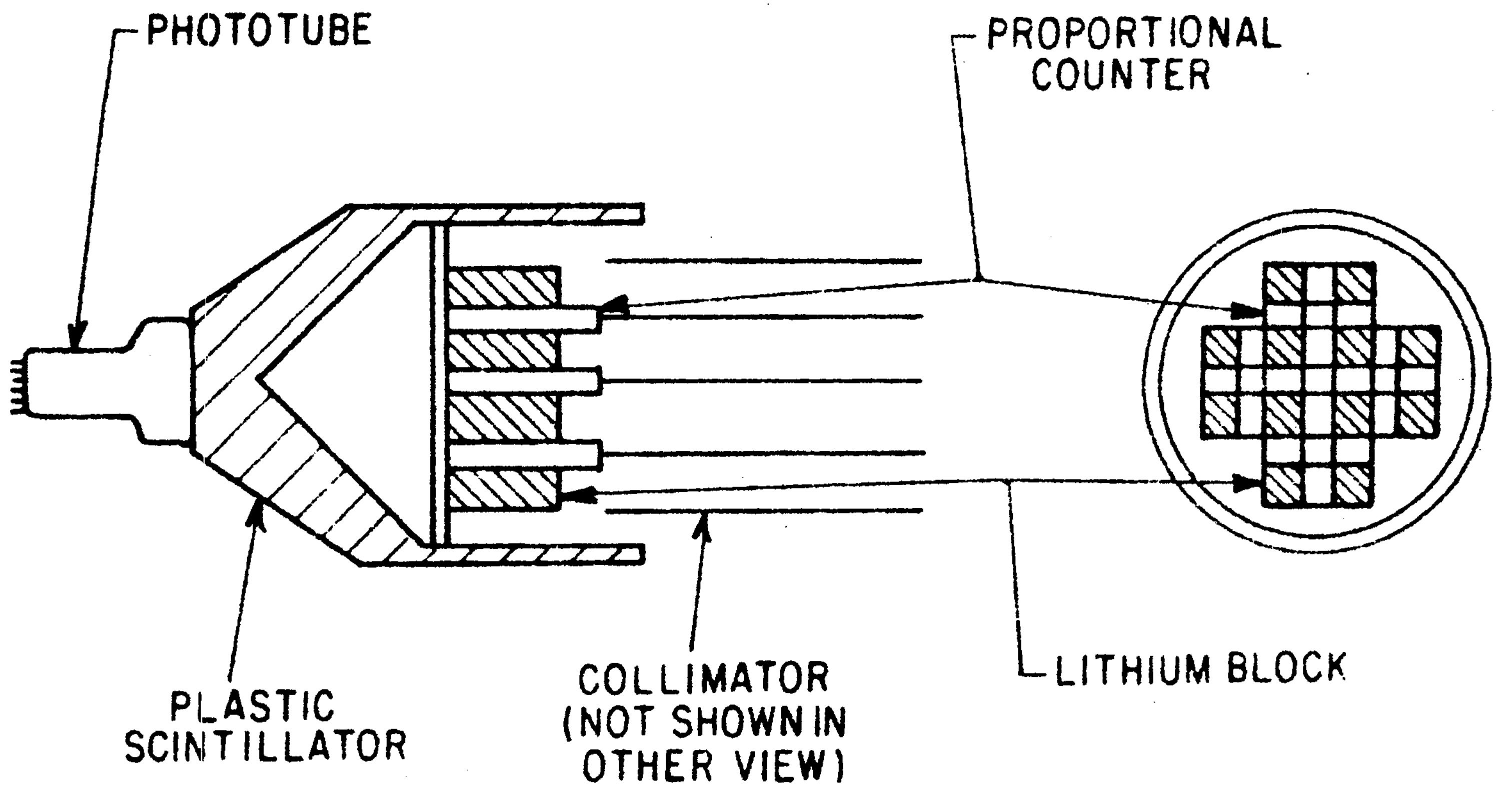
Wolff, R. S., Ph.D. Thesis, Dept. of Physics, Columbia University, New York (1969).

Wolff, R. S., Angel, J. R. P., Novick, R. and Vanden Bout, P., Astrophys. J. Letters 160, L21 (1970).

Woltjer, L., Astrophys. J. 140, 1309 (1964).



1. Sine-squared distribution of scattered photons for two directions of incident polarization. Those scattered within the 90-degree cone carry little information about polarization.



2. Schematic diagram of polarimeter.

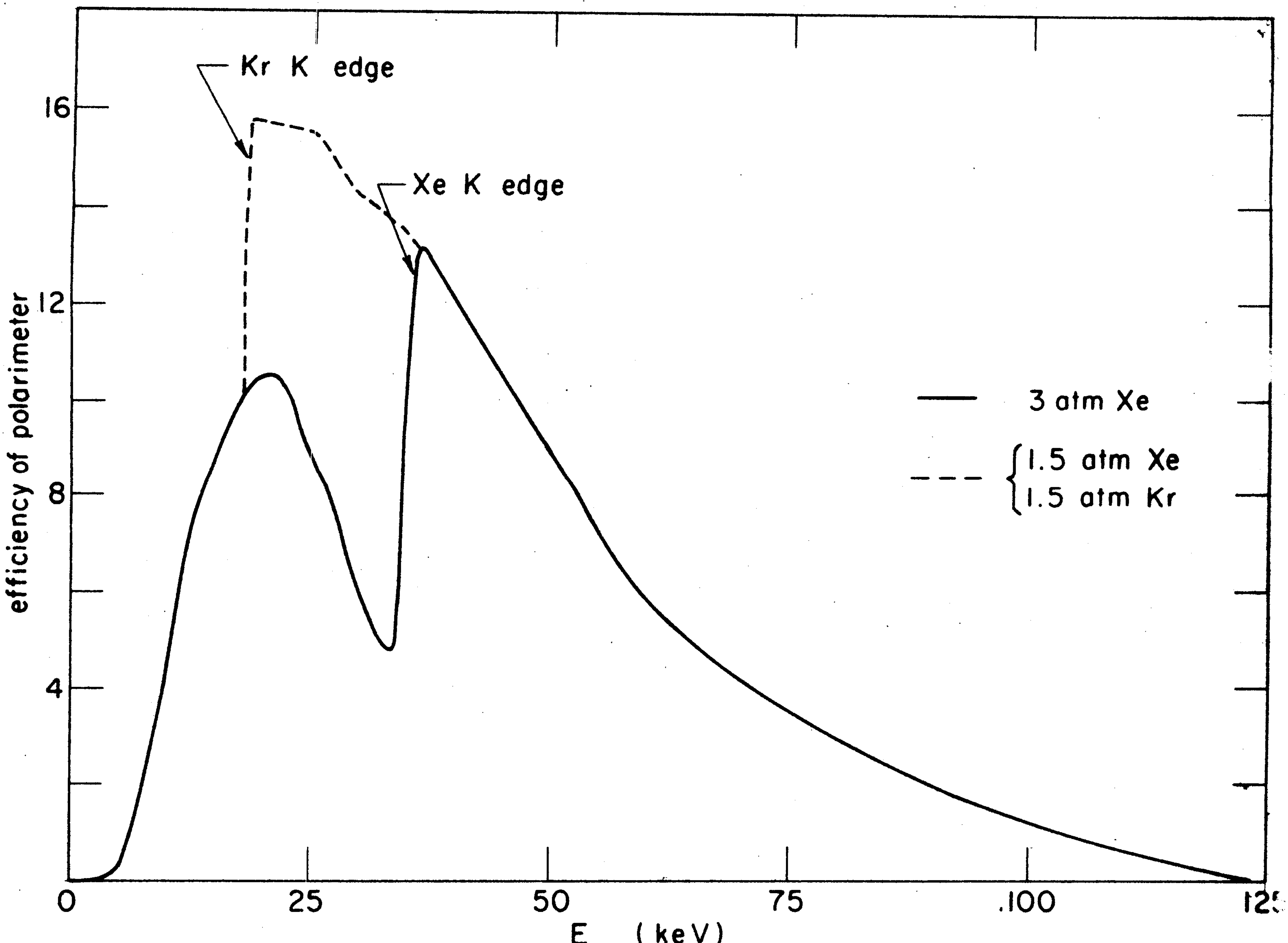


Figure 3: The efficiency of the polarimeter as a function of energy.